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# Technicolor: Status and Prospects

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# Technicolor: Status and Prospects

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**Abstract.** Technicolor models are briefly reviewed, and a number of promising signatures at hadron colliders are described. Low-scale technicolor should be discoverable in Run II of the Fermilab Tevatron; failing that, it would be hard to miss at the LHC. While technicolor models may be unfashionable, it is important to search for their signatures; we do not know how nature has chosen to break electroweak symmetry.

## 1. What is Technicolor?

Though the standard model works extremely well, and is tested at the level of $\sim 10^{-3}$, the detailed mechanism underlying electroweak symmetry breaking remains unknown. In the standard model, the $SU(2) \times U(1)$ electroweak gauge symmetry is spontaneously broken because an elementary scalar field, the Higgs boson, acquires a vacuum expectation value $\langle \phi \rangle \equiv v = 2^{-\frac{1}{4}} G_F^{\frac{1}{2}} = 246\,\mathrm{GeV}$. For several reasons, this electroweak breaking via an elementary Higgs field is regarded as deeply unsatisfactory. In technicolor models, electroweak symmetry is broken dynamically, by a new strong gauge force whose characteristic scale is $\Lambda_{TC} \sim 1$ TeV[1]. Composite bound states of "technifermions" replace the elementary scalars. There is no solid evidence for the course that nature chooses—elementary scalars, possibly augmented with supersymmetry, or composites bound by a new strong interaction. The mysteries of flavor symmetry breaking—why the quark and lepton flavors exist and yet have different masses and complicated mixings—is also completely ignored in the standard model.

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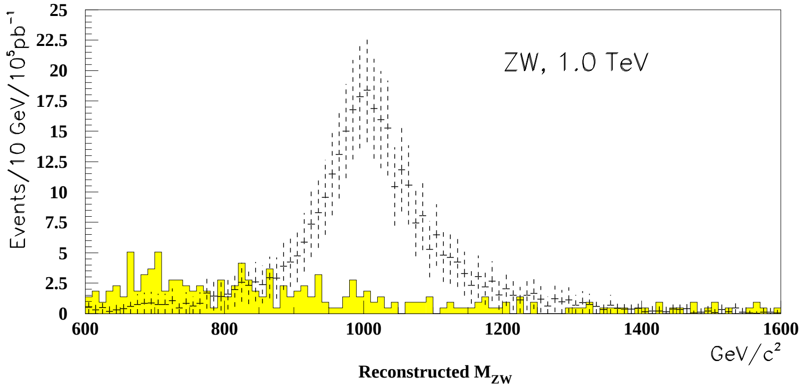
In its simplest form, technicolor is modelled on QCD, following the observation that QCD itself would break electroweak symmetry in the absence of a Higgs. The $W/Z$ mass ratio would even be correct, but the masses would be $\mathcal{O}(50$ MeV$)$. Technicolor simply scales up this behavior and introduces new fermions ("technifermions"). The chiral symmetry of the technifermions, in left-handed $SU(2)$ doublets and right-handed singlets, is broken, and $W$ and $Z$ masses ($m_W, m_Z = 81, 90$ GeV) are generated. The minimal technicolor model contains just a single doublet $(U, D)$ of technifermions. In this case the most accessible physical degree of freedom, apart from from the longitudinal modes of the $W$ and $Z$, is a vector technirho ($\rho_T$) resonance that could be observed as an $s$-channel enhancement in $WW$ and $WZ$ production. Its mass would be expected to be $\sim 1.5-2$ TeV.

Figure 1 shows an example of such a signature at the LHC, taken from [2].

More interesting are non-minimal models such as the one-family model where the technifermions are $(U_c, D_c, N_\ell, E_\ell)$; the subscripts indicate that $U$ and $D$ carry QCD color as well as technicolor, and the $N$ and $E$ technifermions carry lepton number as well as technicolor. Sixty-three Goldstone-boson bound-states of these technifermions, including color-singlet technipions $(\pi_T^\pm, \pi_T^0)$, color octet states, and leptoquark states, would be present with masses of 100–500 GeV. Three of these form the longitudinal $W$ and $Z$ modes; the rest remain to be observed.

In this picture there is no Higgs to generate quark and lepton masses from its Yukawa couplings. Rather, an "extended technicolor" (ETC) gauge interaction is introduced to couple the quarks and leptons to technifermions[3]. The dynamical masses of the technifermions feed down into the masses of the fermions: $m_{q,\ell} \sim \Lambda_{TC}^3/M_{ETC}^2$, where the scale $M_{ETC} \gtrsim 100\,$TeV is the energy at which the ETC gauge group breaks down to flavor, color and technicolor. This ETC picture has severe problems if it is naively scaled from QCD: if unwanted flavor-changing neutral currents interactions, such as contribute to the $K_L$–$K_S$ mass difference, are to be sufficiently suppressed, the quark and lepton masses must be at the MeV scale or less and the technipion masses at a few GeV. These problems can be resolved if the technicolor gauge coupling behaves not like that of QCD but runs much more slowly ("walks", hence this scheme is referred to as "walking technicolor"[4]). Walking can occur if there are a large number of technifermions. This happens, for example, if there is more than one representation of the technicolor group ("multiscale technicolor")[5]. Quark and lepton masses of a few GeV can then be generated together with technipion masses above 100 GeV, all from ETC at the 100 TeV scale.

Generating the large mass of the top quark is still rather difficult in this scheme; we shall return to this issue later.



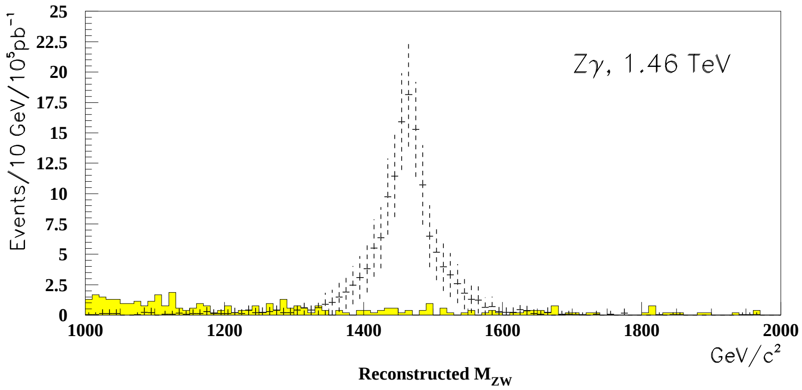




**Figure 1.** Invariant mass distributions for high mass resonances decaying into gauge boson pairs at the LHC, and standard model background (shaded); (a) $\rho_T \rightarrow WZ$ and (b) $\omega_T \rightarrow Z\gamma$.

## 2. Signatures

Technicolor signatures have been reviewed extensively [5, 6, 7]. They include production of dijet resonances (e.g. from color octet technirho states) and the pair production of technipions and/or electroweak vector bosons.

### 2.1. Color-octet Technirho

Color-octet technirhos $\rho_{T8}$ would be expected to have masses between about 200 and 600 GeV and, being colored, would be strongly produced in $qq$ and $gg$ collisions. The cross section should be $\sigma \sim 1 - 10$ pb at the Tevatron and $1 - 10$ nb at the LHC. Various decay modes are possible:

- $\rho_{T8} \rightarrow \pi_T \pi_T \rightarrow 4$ jets ($b$ or $t$);
- $\rho_{T8} \rightarrow \pi_{LQ} \pi_{LQ} \rightarrow 2$ leptons $(\tau, \nu)+$ 2 jets ($t$, $b$ or $c$);
- $\rho_{T8} \rightarrow qq, gg$ if the others are kinematically forbidden.

Figure 2 (taken from [7]) shows the latter signature at the Tevatron; the mass reach is estimated to be 800–900 GeV with 2 $\mathrm{fb}^{-1}$ of data[8].

### 2.2. Technieta

A technieta particle, again with mass expected to lie between about 200 and 600 GeV, could be observed in its decay to $t\bar{t}$ as a resonance in the top-pair invariant mass. The cross section should be $\sigma \sim 1 - 10$ pb at the Tevatron and $1 - 10$ nb at the LHC, making it straightforward to observe.

### 2.3. Pair-production of technipions

Here we present some new calculations of these signatures, which appear to be the most accessible at present accelerators.

Light, color-singlet technipions, $\pi_T^{\pm}$ and $\pi_T^0$, are expected to occur in models of multiscale technicolor. These technipions will be resonantly produced via technivector meson dominance at substantial rates at the Tevatron and the Large Hadron Collider. The technivector mesons in question are an isotriplet of color-singlet $\rho_T$ and the isoscalar partner $\omega_T$. Because techni-isospin is likely to be a good approximate symmetry, $\rho_T$ and $\omega_T$ should have equal masses as do the various technipions. We shall assume that the channels $\rho_T \rightarrow \pi_T \pi_T$ and $\omega_T \rightarrow \pi_T \pi_T \pi_T$ are closed (as would be suggested in walking technicolor models where the technipion masses are enhanced). Thus, the decay modes $\rho_T \rightarrow W_L \pi_T$ and $Z_L \pi_T$, where $W_L$, $Z_L$ are longitudinal weak bosons, and $\omega_T \rightarrow \gamma \pi_T$ may dominate.

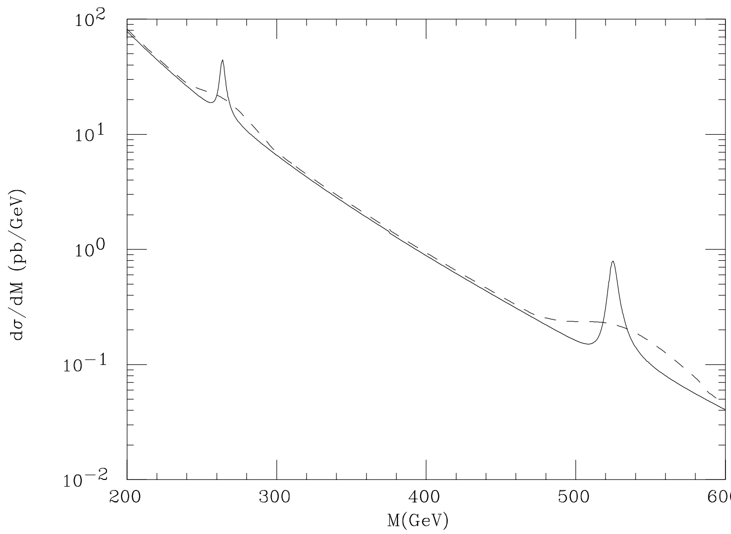



**Figure 2.** Invariant mass distributions for dijets at the Tevatron, showing two masses of color-octet technirho resonance. The solid line is perfect parton resolution and the dashed line represents $100\%/\sqrt{E}$ jet resolution.

We present simulations of $\bar{p}p \to \rho_T^\pm \to W_L^\pm \pi_T^0$ and $\omega_T \to \gamma\pi_T^0$ for the Tevatron collider with $\sqrt{s} = 2\,\text{TeV}$ and an integrated luminosity of $1\,\text{fb}^{-1}$. Although we do not simulate these processes for the LHC, cross sections there are an order of magnitude larger than at the Tevatron, so detection of the light technihadrons should be easy.

### 2.4. The Channel $\rho_T^\pm \to W^\pm \pi_T^0$

We follow the cross sections and decay branching ratios outlined in Refs. [6, 7, 9]. It is assumed that there is just one light isotriplet and isoscalar of color-singlet technihadrons and a simple model of technirho production and decay is used to determine the rates of the processes

$$\begin{array}{llllll} q\bar{q}' & \to W^\pm & \to \rho_T^\pm & \to & W_L^\pm Z_L^0; \quad W_L^\pm \pi_T^0,\ \pi_T^\pm Z_L^0; & \pi_T^\pm \pi_T^0 \\ q\bar{q} & \to \gamma, Z^0 & \to \rho_T^0 & \to & W_L^+ W_L^-; \quad W_L^\pm \pi_T^\mp; & \pi_T^+ \pi_T^- \end{array} \tag{1}$$

and their dependence on $M_{\rho_T}$. Here we shall focus on technirho decay modes with the best signal-to-background ratios, namely, $\rho_T \to W_L \pi_T$ or $Z_L \pi_T$. For definiteness, we assume $M_{\rho_T} = 210\,\text{GeV}$ and $M_{\pi_T} = 110\,\text{GeV}$; $\sin\chi = \frac{1}{3}$, where $\chi$ is the mixing angle between $\pi_T$ and $W_L$; and $N_{TC}$, the number of technicolors, to be 4.

Technipion couplings to fermions are expected to be proportional to mass. We adhere to that expectation and assume that technipions decay as

$$\begin{array}{ll} \pi_T^0 & \to b\bar{b} \\ \pi_T^+ & \to c\bar{b} \text{ or } c\bar{s},\ \tau^+\nu_\tau\,. \end{array} \tag{2}$$

Thus, heavy-quark jet tagging is an important aid to technipion searches.[2]

We have used PYTHIA 6.1 [10] to generate $\bar{p}p \to W^\pm \to \rho_T^\pm \to W^\pm \pi_T^0$ with $\pi_T^0 \to \bar{b}b$ at the Tevatron Collider with $\sqrt{s} = 2\,\text{TeV}$. With our choice of parameters, the cross section for this process is 5.3 pb. We also used PYTHIA to generate the $W^\pm$ jet jet background. Jets were found using the clustering code provided in PYTHIA with a cell size of $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$, a cone radius $R = 0.7$ and a minimum jet $E_T$ of 5 GeV. Cell energies were smeared using a calorimeter resolution of $0.5\sqrt{E(\text{GeV})}$. Missing transverse energy $\not{E}_T$ was then calculated from the vector sum of $E_T$ over all found jets and leptons. Selected events were required to have an isolated electron or muon, large missing energy, and two or more jets:

- Lepton: $E_T(\ell) > 25\,\text{GeV}$; pseudorapidity $|\eta| < 1.1$.

[2] We note that some topcolor-assisted technicolor models [13] have the feature that certain technifermions, and their bound-state technipions, couple mainly to the lighter fermions of the first two generations. The flavor-blind kinematical cuts we discuss below will be essential for this possibility.

- Missing energy: $\not{E}_T > 25\,\mathrm{GeV}$.
- Transverse mass: $50\,\mathrm{GeV} < \mathcal{M}_T(\ell \not{E}_T) < 100\,\mathrm{GeV}$.
- Two or more jets with $E_T > 20\,\mathrm{GeV}$ and $|\eta| < 2.0$, separated from the lepton by at least $\Delta R = 0.7$.

Requiring that the lepton and jets be central in pseudorapidity exploits the fact that the signal events will tend to be produced with larger center-of-mass scattering angles than the background. Figure 3(a) shows the invariant mass distribution of the two highest-$E_T$ jets for the signal (black) and background (grey) events passing these criteria for a luminosity of $1\,\mathrm{fb}^{-1}$, half that expected in Tevatron Run II.

The peculiar kinematics of $\rho_T \to W_L \pi_T$ and $Z_L \pi_T$ suggest other cuts that can discriminate signals from the $W/Z +$jets backgrounds.[3] The $\pi_T$ and $W_L$ (or $Z_L$) have $p_T < p_T^{\mathrm{max}} \simeq 45\,\mathrm{GeV}$ for our reference masses, and the jets are emitted with an opening azimuthal angle $\Delta\phi(jj) \gtrsim 140^\circ$. These expectations were borne out by simulated distributions in these variables. Consequently, we have taken the selected events in Fig. 3(a) and applied the additional topological cuts $\Delta\phi(jj) > 125^\circ$ and $20 < p_T(jj) < 50\,\mathrm{GeV}$. These cuts reject 78% of the $Wjj$ background while retaining 64% of the signal. The results are shown in Fig. 3(b). For the signal cross section of 5.3 pb, the signal-to-background at 100 GeV is improved from 0.04 to 0.11 by these cuts. A signal rate in excess of 15 pb would produce a visible excess at this level.

The additional effect of tagging one $b$-jet per event is shown in Fig. 3(c). We have assumed a 50% efficiency for tagging $b$'s, a 1% probability to mistag light quarks and gluons, and a 17% probability to mistag charm as a $b$. This final selection leaves a clear dijet resonance signal above the background at just below the mass of the $\pi_T$. For $80 < m_{jj} < 120\,\mathrm{GeV}$, there are 65 signal events over a background of 35. The mass distribution for the signal is almost gaussian, with a peak at 97 GeV and $\sigma \simeq 12.7\,\mathrm{GeV}$. This width and a tail on the low side are due mainly to the effects of final-state gluon radiation, fragmentation, calorimeter resolution and neutrinos from $b$-decay.

Figure 3(d) shows the invariant mass distributions for the $Wjj$ system after topological cuts and $b$-tagging have been imposed. Here the $W$ four-momentum was reconstructed from the lepton and $\not{E}_T$, taking the lower-rapidity solution in each case. Again, a clear peak is visible at just below the mass of the $\rho_T$. We point out that, especially after making the topological

[3] The following discussion applies to both the Tevatron and the LHC but, because of the smaller boost rapidities of the $\rho_T$ at the Tevatron, signal events will be more central there. Cutting harder on rapidity for LHC events will improve signal-to-background; the higher cross section and luminosity at the LHC leave plenty of events.

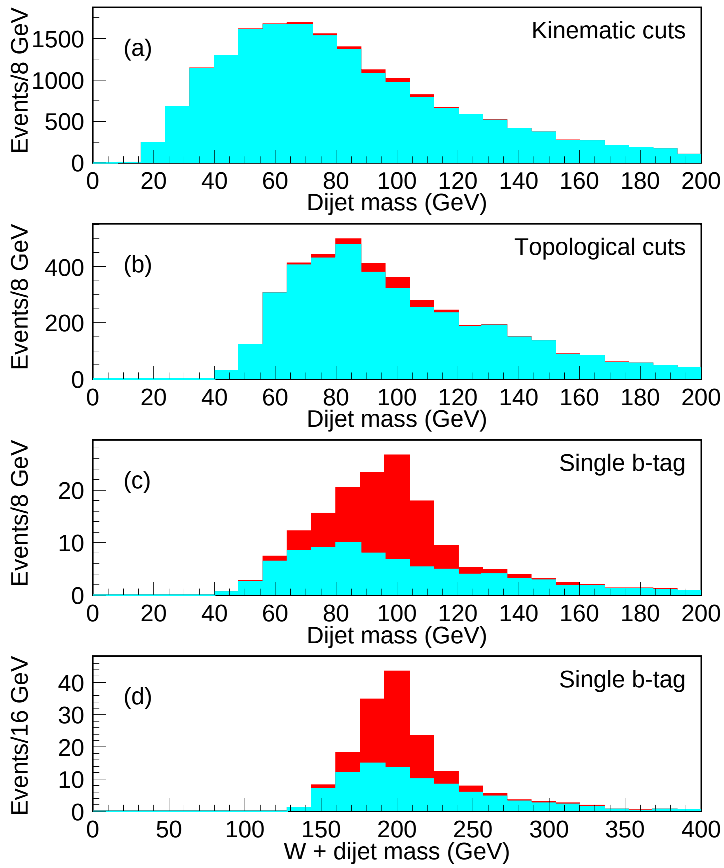



**Figure 3.** Invariant mass distributions for $\rho_T$ signal (black) and $Wjj$ background (grey); vertical scale is events per bin in 1 fb$^{-1}$ of integrated luminosity. Dijet mass distributions (a) with kinematic selections only, (b) with the addition of topological selections, and (c) with the addition of single $b$-tagging; (d) $W$+dijet invariant mass distribution for the same sample as (c).

cuts, the dijet mass and the $Wjj$ mass are highly correlated; a peak in one distribution is almost bound to correspond to a peak in the other. Thus, the existence of structure in both distributions does not add to the statistical significance of any observation.

We conclude that if $\rho_T$ and $\pi_T$ exist in the mass range we consider, they can be found without difficulty in Run II of the Tevatron. In fact, since there are $\sim 65$ signal events in Fig. 3(c) for $\sigma(\rho_T^\pm \to W^\pm \pi_T^0) \simeq 5\,\mathrm{pb}$, one might see hints of a signal with one tenth the luminosity. It is certainly worth looking in the presently accumulated samples of $\sim 100\,\mathrm{pb}^{-1}$ per experiment. The production cross section at $1.8\,\mathrm{TeV}$ is about 15% lower than at $2.0\,\mathrm{TeV}$. Other channels may also add to the cross section: for our reference masses, $\rho_T^0 \to W^\pm \pi_T^\mp$ contributes an additional $2.3\,\mathrm{pb}$, though only one $b$-jet is present in the $\pi_T^\pm$ decay.

Both CDF and DØ have presented preliminary results on such searches which are described elsewhere in these proceedings. No signal has been observed but the cross section upper limits are currently $\sim 20 - 30$ pb which is close to the required sensitivity (Fig. 4).

### *2.5. The Channel* $\omega_T \to \gamma \pi_T^0$

The $\omega_T$ is produced in hadron collisions just as the $\rho_T^0$, via its vector-meson-dominance coupling to $\gamma$ and $Z^0$. Its cross section is proportional to $|Q_U + Q_D|^2$, where $Q_{U,D}$ are the electric charges of the $\omega_T$'s constituent technifermions. For $M_{\omega_T} \simeq M_{\rho_T}$, then, the $\omega_T$ and $\rho_T^0$ should be produced at comparable rates, barring accidental cancellations. If the $\rho_T \to \pi_T \pi_T$ channels are nearly or fully closed, then $\omega_T \to \pi_T \pi_T \pi_T$ certainly is forbidden. If we can use decays of the ordinary $\omega$ as a guide, $\omega_T \to \gamma \pi_T^0$, $Z^0 \pi_T^0$ will be much more important than $\omega_T \to \pi_T \pi_T$ [6]. It is not possible to estimate the relative importance of these two modes without an an explicit model, but it seems plausible that $\gamma \pi_T^0$ will dominate the phase-space-limited $Z^0 \pi_T^0$ channel. Therefore, we concentrate on the $\omega_T \to \gamma \pi_T^0 \to \gamma b \bar{b}$ mode in this paper. The mass parameter $M_T$ in the $\omega_T \to \gamma \pi_T^0$ rate is unknown *a priori*; we take it to be $M_T = 100\,\mathrm{GeV}$ in our calculations. We also took the technifermion charges to be $Q_U = \frac{4}{3}$ and $Q_D = Q_U - 1 = \frac{1}{3}$, and we used $M_{\omega_T} = M_{\rho_T} = 210\,\mathrm{GeV}$ and $M_{\pi_T} = 110\,\mathrm{GeV}$.

PYTHIA 6.1 [10] was used to generate $\bar{p}p \to \gamma, Z^0 \to \omega_T \to \gamma \pi_T^0$ with $\pi_T^0 \to \bar{b}b$ at $\sqrt{s} = 2\,\mathrm{TeV}$. The cross section for this process is $2.6\,\mathrm{pb}$. The background considered is $\gamma$ jet jet. Selected events were required to have an isolated photon and two or more jets. The selection criteria were:

- Photon: $E_T(\gamma) > 50\,\mathrm{GeV}$; pseudorapidity $|\eta| < 1.1$.
- Two or more jets with $E_T > 20\,\mathrm{GeV}$ and $|\eta| < 2.0$, separated from the photon by at least $\Delta R = 0.7$.

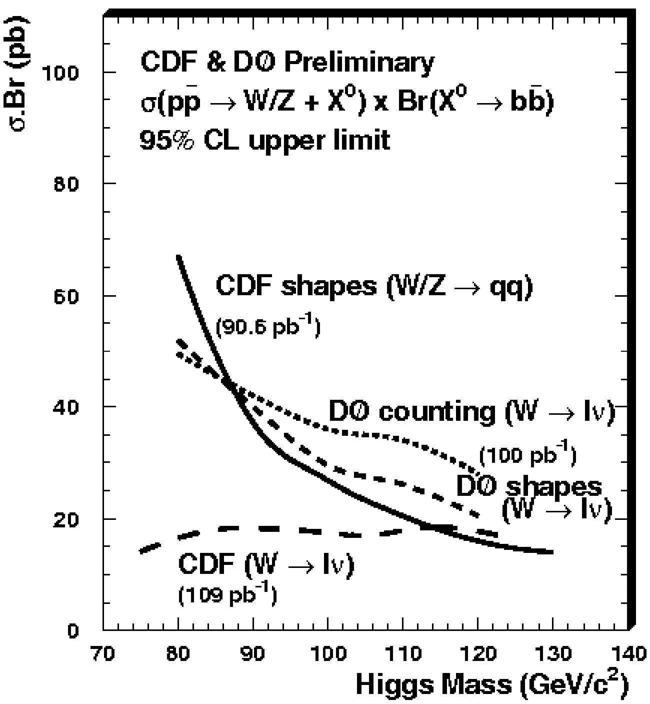



**Figure 4.** Present preliminary limits from CDF and DØ on the cross section for $p\overline{p} \rightarrow (W/Z)X$ with $X \rightarrow b\overline{b}$.

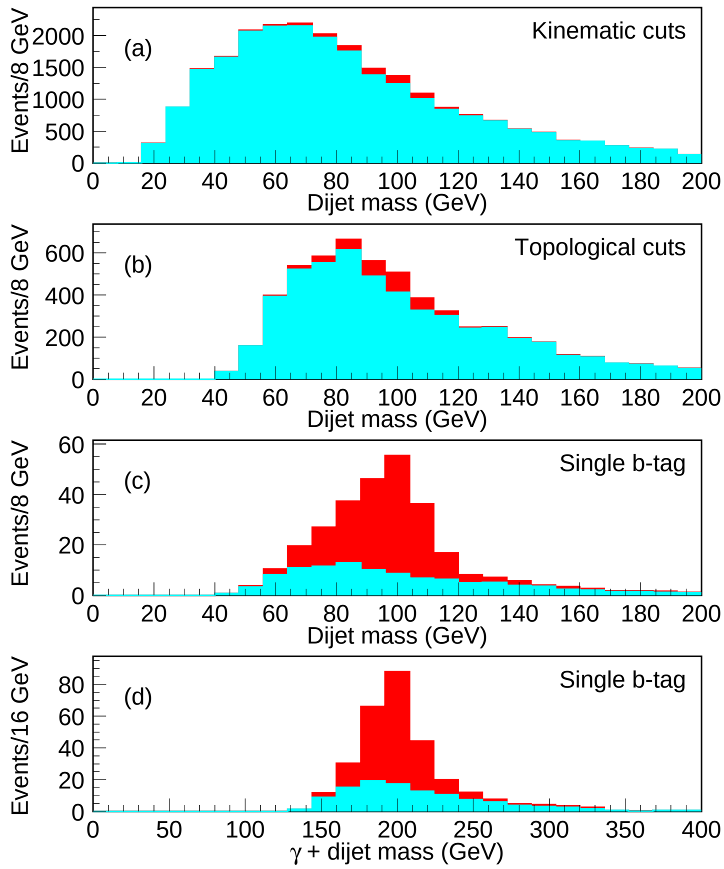



**Figure 5.** Invariant mass distributions for $\omega_T$ signal (black) and $\gamma jj$ background (grey); vertical scale is events per bin in 1 $\mathrm{fb}^{-1}$ of integrated luminosity. Dijet mass distributions (a) with kinematic selections only, (b) with the addition of topological selections, and (c) with the addition of single $b$-tagging; (d) $\gamma$+dijet invariant mass distribution for the same sample as (c).

Figure 5(a) shows the invariant mass distribution of the two highest-$E_T$ jets for the signal (black) and background (grey) events passing these criteria for an integrated luminosity of $1\,\mathrm{fb}^{-1}$. As for the $\rho_T$, backgrounds swamp the signal. Therefore, we have again investigated topological selections which might enhance the signal over the backgrounds. For $M_{\omega_T} \simeq 200\,\mathrm{GeV}$ and $M_{\pi_T} \simeq 100\,\mathrm{GeV}$, signal events have $p_T \lesssim 75\,\mathrm{GeV}$ and dijet azimuthal angle $\Delta\phi(jj) \gtrsim 105°$. We apply the additional cut $\Delta\phi(jj) > 90°$ to the untagged events of Fig. 5(a). However, no useful cut can made on $p_T(jj)$ since the signal and background have very similar shapes.

The effect of these cuts is seen in Fig. 5(b). The $\gamma jj$ background is reduced by 61% while 75% of the signal is retained. Tagging one $b$-jet further improves the signal/background as shown in Fig. 5(c), and a clear peak just below the $\pi_T$ mass can be seen. Figure 5(d) shows the photon+dijet invariant mass after the topological cuts and $b$-tagging are employed. Again, we found that this total invariant mass was not a useful variable to cut on.

### *2.6. The channel* $\omega_T \to \ell^+\ell^-$

The process $p\overline{p} \to \omega_T \to \ell^+\ell^-$ is an interesting possibility. The cross section may be significant ($\gtrsim 0.1$ pb) at the Tevatron, and the good dilepton mass resolution of the CDF and DØ detectors would give a clear signal with a small and well-understood Drell-Yan background. Existing CDF data may in fact already provide a constraint. This channel therefore merits further investigation.

### *2.7. Signatures at LEP2*

Production of new technicolor particles at LEP2 is unlikely. The best hope is $e^+e^- \to \omega_T \to f\overline{f}$ provided the mass of the $\omega_T$ is less than $\sqrt{s}$. The signal would be clear and spectacular.

## 3. What about the top quark?

As mentioned earlier, the large mass of the top quark is troublesome to accommodate in the ETC framework. It is hard to generate a sufficiently large mass without violating precision electroweak measurements (the $\rho$ parameter and $Z \to b\overline{b}$ branching ratio). Is this large mass trying to tell us something? It has been suggested that the top quark is itself a player in electroweak symmetry breaking [11]. Since ETC models generate masses dynamically, a natural interpretation is that the large top mass indicates that the top quark has some unique dynamics. This leads to a class of models called "topcolor"[12] and topcolor-assisted technicolor ($\mathrm{TC}^2$)[13].

In TC$^2$ models, the Standard Model SU(3)×U(1) gauge groups are replaced by $SU(3)_{1,2} \times SU(3)_3 \times U(1)_{1,2} \times U(1)_3$ (where the subscripts denote preferential couplings to the first and second, and to the third, generation). This breaks down to ordinary SU(3)×U(1) at $\sim$ 1 TeV. The third-generation SU(3) is the topcolor interaction; it generates a dynamical component of the top mass and is responsible for its being so large. The third-generation U(1) keeps the $b$-quark relatively light. In this picture the light quark masses (and a small contribution to $m_t$) are still generated from ETC at the 100 TeV scale, and electroweak symmetry breaking is still largely due to technicolor.

Topcolor-assisted technicolor is quite new and its phenomenology has not been fully explored. Nonetheless we expect all the previous signatures of multiscale technicolor plus:

- An isotriplet of "top-pions" $\pi_t$ from the breakdown of the third-generation SU(3)×U(1). These would be produced in top decays, or themselves decay into top, depending on their mass.

- A "top-rho" $\rho_t$ with a mass between about $2m_t$ and 1 TeV, decaying to pairs of top-pions or maybe to $t\bar{t}$ or $b\bar{b}$.

- A color-octet gauge boson $V_8$ ("coloron" or "top-gluon") with a mass 0.5–2 TeV, probably a large width (, $/m \sim 0.5$), and a production cross section of 1–10 pb at the Tevatron and 100 pb – 1 nb at the LHC. This could be observed as resonances in $b\bar{b}$ or $t\bar{t}$ invariant mass. The reach in mass is estimated to be 800 GeV – 1 TeV with 2 fb$^{-1}$ of data at the Tevatron[8].

- A $Z'$ vector boson associated with the breakdown of the third-generation U(1), with a mass 1–3 TeV. It might be narrow, and could be observed as a resonances in the $t\bar{t}$ invariant mass. It was even suggested that it might couple strongly to the first and second generations as well as the third and hence provide a signal in high-$E_T$ jets (motivated by CDF's apparent excess). Again, the reach in mass is estimated to be 800 GeV – 1 TeV (depending on the width) with 2 fb$^{-1}$ of data at the Tevatron[8].

## 4. Conclusion

A number of low-scale technicolor signatures have been described; many can be discovered easily in Run II of the Tevatron. The production rates are an order of magnitude higher at the LHC than at the Tevatron. Thus, the LHC will be decisive in excluding low-scale technicolor signatures of the type considered here.

It is important to remember that new physics is not necessarily synonymous with supersymmetry. Though technicolor models are not fashionable (and indeed may have potential conflicts with precision electroweak measurements), something like this could be the way nature has chosen to break electroweak symmetry. We need to do the experiments, and let the data be the judge.

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